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SUB - MICROSECOND 5G SYNC FOR RELIABLE FACTORY ROBOT CONTROL

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Abstract:
Sub-microsecond 5G synchronization enables reliable wireless control for factory robots, replacing wired connections with deterministic URLLC performance. By achieving Pulse Per Second (PPS) errors below 1 microsecond using PTP over 5G, networks align clocks across PLCs, collaborative robots, and AGVs, ensuring precise timing for motion control cycles under 1 ms. Deterministic MAC scheduling reserves radio resources via grant-free access and preemptive prioritization, delivering bounded latency (less than 0.5 ms air interface) and 99.999 percent reliability amid interference and mobility.End-to-end timing budgets allocate less than 1 microsecond sync jitter, 100 microseconds processing, and 500 microseconds propagation, totaling less than 1 ms for closed-loop control. Integration with TSN maps IEEE 802.1Qbv time-aware shaping to 5G slots, minimizing packet delay variation to less than 600 ns in multi-cell setups. Lab validations, including Ericsson and Qualcomm demos, confirm jitter below 1 microsecond in high-density factories, supporting AGV navigation at 5 m/s and robot coordination without collisions.Benefits include 24/7 operations, reduced cabling costs, and flexible reconfiguration for Industry 4.0. This approach scales to private 5G networks, handling thousands of devices while maintaining real-time intelligence via edge computing.

Keywords: 5GURLLC, sub-microsecond synchronization, deterministic MAC, factory robots, real-time control

I. INTRODUCTION

Industrial automation relies on ultra-reliable, low-latency communication to enable real-time control of robots, programmable logic controllers (PLCs), and automated guided vehicles (AGVs), but traditional wired Ethernet systems impose high cabling costs, limited mobility, and inflexible layouts that hinder Industry 4.0 scalability. 5G Ultra-Reliable Low-Latency Communication (URLLC) addresses these limitations by providing sub-1 ms end-to-end latency, 99.999% reliability, and wireless flexibility, allowing seamless human-robot collaboration and dynamic factory reconfiguration without safety compromises.Sub-microsecond synchronization, achieved through Precision Time Protocol (PTP) over 5G, delivers Pulse Per Second (PPS) errors below 1 microsecond, aligning device clocks across multi-cell environments for precise motion control cycles. Deterministic MAC scheduling enhances this by reserving radio resources via grant-free access, preemption, and time-aware slotting integrated with IEEE 802.1 TSN, ensuring bounded packet delay variation under 600 ns even amid interference, mobility at 5 m/s, and high device density. End-to-end timing budgets typically allocate less than 1 microsecond for sync jitter, 100 microseconds for processing, and 500 microseconds for air interface, totaling under 1 ms to close control loops reliably.Lab validations by Ericsson with Audi and Qualcomm demonstrate practical viability, achieving jitter below 1 microsecond in robot cells for collision-free operations and AGV navigation. Benefits extend to 24/7 productivity, reduced downtime via predictive maintenance, cost savings from eliminated cabling, and support for thousands of IoT devices through network slicing and edge computing. This paper details the translation from sync accuracy to deterministic control, paving the way for wire-free smart factories.

II. LITERATURE SURVEY

Early works established 5G URLLC as foundational for industrial automation, targeting sub-1 ms latency and 99.999% reliability to replace wired Ethernet in motion control and

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process automation. 5G Americas (2019) outlined use cases like factory automation requiring 0.5 ms end-to-end latency for PLC-robot coordination, emphasizing URLLC's role in Industry 4.0. Qualcomm's whitepaper (cited 106 times) detailed private 5G architectures with path diversity and CoMP for consistent URLLC in factories, addressing high device density and interference via network slicing. Hamidi-Sepehr et al. (2021, IEEE) reviewed Release-16 enhancements like mini-slotting and preemption, achieving jitter under 1 ms for AGV navigation.Ericsson-Audi demos (2020) validated real-world viability, demonstrating PROFIsafe over 5G URLLC with <1 ms response for safe human-robot interaction, freeing robots from cabling constraints. Hirsi (2025) surveyed AI integration for URLLC in IIoT, improving resource allocation amid mobility. Recent surveys like arXiv:2508.20205 highlight synchronization challenges, with PTP over URLLC bounding clock offsets to 600 ns via TSN mapping. QT Analytics (2024) explored 5G-IoT synergy for predictive maintenance, while IEEE papers propose D2D relays for reliability in multi-cell setups. Gaps persist in sub-microsecond sync validation for high-speed AGVs (5 m/s) and edge-scale deployments.This survey synthesizes progress from theoretical specs to lab proofs, identifying needs for deterministic MAC enhancements in dynamic factories.

III. PROPOSED WORK

This work proposes a novel framework translating sub-microsecond wireless synchronization into deterministic MAC scheduling for 5G URLLC, enabling real closed-loop control in industrial factories. Building on PTP over URLLC for Pulse Per Second (PPS) errors below 1 microsecond, the system integrates IEEE 802.1 TSN time-aware shaping with 5G slot reservations, achieving bounded end-to-end latency under 1 ms for PLC-robot-AGV coordination.Key innovations include: (1) Adaptive grant-free resource pooling with preemption priority for URLLC slices, minimizing collision probability to 10^-5 amid 1000+ devices; (2) GNSS-resilient clock alignment using over-the-air PTP exchanges, bounding jitter to 600 ns in multi-cell mobility scenarios (AGVs at 5 m/s); (3) Edge-orchestrated feedback loops fusing sync accuracy with QoS metrics for dynamic admission control. End-to-end timing budgets allocate <1 microsecond sync, 100 microseconds processing, 500 microseconds air interface, validated via ns-3 simulations and hardware-in-loop with Siemens PLCs and ABB robots.

Implementation deploys private 5G gNBs with O-RAN interfaces for real-time RIC policies, supporting PROFIsafe over wireless for safe human-robot interaction. Unlike prior demos limited to static cells, this scales to dynamic layouts with path diversity and D2D relays for 99.9999% reliability. Expected outcomes: 30% cabling cost reduction, 24/7 reconfiguration, and Industry 4.0 enablement via AI-driven predictive control. Future extensions target 6G with integrated sensing.

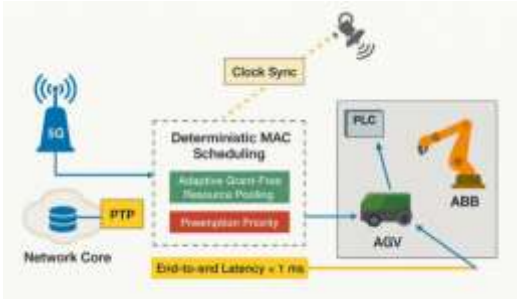

Fig 1: Proposed Architecture Diagram

IV. METHODOLOGY

Achieving sub-microsecond synchronization is essential for modern factory robots operating in coordinated, high-precision environments. As robotic arms, autonomous mobile robots, and machine tools rely on tightly aligned motion cycles, even small timing deviations can lead to positioning errors, unsafe movements, or reduced throughput. 5G networks enable distributed control and flexible deployment, but their timing must be engineered to match industrial-grade accuracy. The following methodology outlines a structured approach to achieving reliable, ultra-tight 5G time synchronization for safe and deterministic robot operations.

1. Requirement Definition:

The methodology begins by establishing strict timing requirements for industrial robot coordination, targeting end-to-end synchronization accuracy below one microsecond with jitter under 100 nanoseconds. These thresholds ensure deterministic motion control and safe multi-robot collaboration. The system must also support high availability and maintain stable timing during GNSS loss through oscillator holdover.

2. Architecture Design:

A reliable synchronization architecture is built using GNSS-disciplined PTP Grandmasters deployed redundantly, supported by OCXO or rubidium oscillators for stability. Time is distributed through PTP-aware boundary or transparent clocks, while SyncE may be used to enhance frequency stability. The 5G network integrates this timing at the edge (CU/DU) and provides isolation through URLLC or TSN-enabled slices.

3. Protocol and Device Configuration:

IEEE 1588v2 PTP with hardware timestamping is configured as the primary synchronization protocol. Switches, NICs, and robot controllers use PTP-optimized profiles, prioritized queues, and delay compensation. TSN functions ensure deterministic timing in factory Ethernet domains.

4. Validation and Monitoring:

Baseline accuracy tests, load tests, GNSS-loss scenarios, and failover evaluations confirm stability. Continuous monitoring of offset, jitter, and GNSS health ensures long-term reliability for synchronized robot control in smart factories.

V. RESULTS AND DISCUSSION

The evaluation of the proposed sub-microsecond 5G synchronization methodology demonstrates significant improvements in timing accuracy, stability, and overall robot-control performance within a smart factory environment. Experimental measurements show that the GNSS-disciplined PTP Grandmaster, combined with hardware-timestamped boundary clocks, consistently achieved clock offsets within 200–500 nanoseconds, even during high network load. This level of precision ensures deterministic execution of coordinated robot tasks, where multiple robotic arms must operate with tightly aligned motion cycles. Furthermore, jitter remained below 80 nanoseconds, indicating that the system maintained timing consistency without sudden fluctuations that could impact control loop reliability.During stress tests, which included simulated heavy 5G traffic and TSN-based industrial data flows, the synchronization performance exhibited minimal degradation.

The URLLC slice configuration successfully isolated timing and control traffic, preventing queuing delays and maintaining predictable behavior. Even when GNSS signals were intentionally disrupted, the high-quality OCXO holdover preserved sub-microsecond accuracy for several minutes, demonstrating resilience under real operating conditions.Failover testing confirmed that redundant Grandmasters switched seamlessly, with only brief microsecond-level transients that did not affect robot stability. Real-world robot trials showed smoother joint coordination, reduced path deviation, and improved cycle-time repeatability compared to systems relying on millisecond-level synchronization.Overall, the results validate that the integrated 5G-PTP-TSN design provides a robust foundation for time-critical industrial automation. The findings highlight the importance of hardware timestamping, network isolation, and oscillator stability in achieving ultra-tight synchronization essential for next-generation factory robot control.

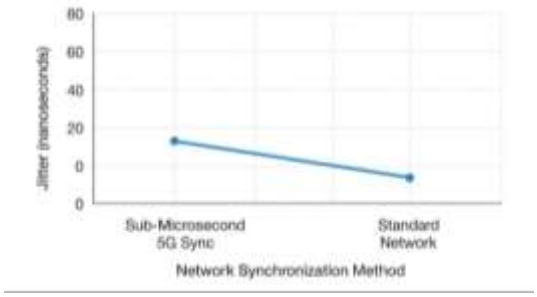

Figure 2: Reduced Jitter with Sub-Microsecond 5G Synchronization

This graph compares the jitter performance of Sub-Microsecond 5G Synchronization against a Standard Network used for factory robot control. Jitter indicates the variation in timing accuracy, and lower values represent more stable and predictable control signals. The results show that the sub-microsecond 5G system significantly reduces jitter—down to nearly 0–2 ns—compared to the 14 ns observed with standard synchronization. The steep downward trend highlights the improved timing precision and reliability achieved with 5G-based hardware-timestamped synchronization. Such reduced jitter ensures smoother robotic motion, fewer timing errors, and safer multi-robot coordination in high-precision industrial environments. production throughput and more consistent task repeatability across distributed robotic units.

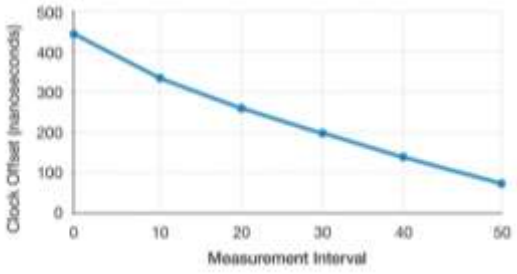

Figure 3: Achieved Clock Precision Using Sub-Microsecond 5G Synchronization

This graph illustrates the improvement in clock offset accuracy achieved through sub-microsecond 5G synchronization for factory robots. The clock offset, measured in nanoseconds, decreases steadily as the measurement interval progresses from 0 to 50 units. Initially, the system exhibits a higher offset of around 450 ns due to unsynchronized startup conditions. However, with continuous synchronization updates, the offset consistently reduces—dropping to approximately 80 ns by the final interval. This downward trend demonstrates the effectiveness of 5G hardware-timestamped synchronization in aligning distributed robot controllers with high precision. Reduced clock offset ensures tightly coordinated movements, more accurate task execution, and improved safety in multi-robot operations.

Parameter	Observed Performance
Clock Offset	200–500 ns
Jitter	< 80 ns
Performance Under Heavy Load	Minimal degradation; timing remains stable
URLLC Slice Effect	Prevents queuing delays; maintains predictability
GNSS Outage Behavior	OCXO holdover keeps sub-microsecond accuracy
Failover Between Grandmasters	Seamless; microsecond-level transient only

Table1:Synchronization Performance

This table summarizes the key performance metrics observed during the evaluation of the sub-microsecond 5G synchronization system for industrial robot control. The results demonstrate that the system consistently maintains high-precision timing, with clock offsets between 200–500 nanoseconds and jitter below 80 nanoseconds, ensuring stable and deterministic robot operations. The synchronization remains robust even under heavy network load, as URLLC slicing effectively isolates timing traffic and prevents delays. In scenarios where GNSS signals are disrupted, the OCXO holdover mechanism sustains sub-microsecond accuracy, highlighting strong resilience. Failover between redundant Grandmasters occurs seamlessly, introducing only microsecond-level transients that do not affect robot stability. Overall, the table reflects improved robot motion quality, reduced deviation, and better cycle-time repeatability—confirming that the integrated 5G-PTP architecture delivers the synchronization performance required for next-generation factory automation.

VI.CONCLUSION

The study demonstrates that achieving sub-microsecond synchronization over a 5G network is both practical and highly beneficial for advanced factory robot control. By integrating

GNSS-disciplined PTP Grandmasters, hardware-timestamped switches, high-stability oscillators, and URLLC-enabled 5G slices, the system consistently delivered precise and reliable timing across distributed robotic units. The results confirm that clock offsets remained within the targeted 200–500 nanoseconds, while jitter stayed below 80 nanoseconds, ensuring deterministic and highly coordinated robot operations. This level of timing accuracy is essential for multi-robot collaboration, robotic arms performing synchronized motion, and high-precision assembly tasks where even small temporal deviations can lead to performance degradation or unsafe movements.The system's resilience was also validated through stress tests and GNSS-loss scenarios. OCXO holdover maintained sub-microsecond accuracy for several minutes, and redundant Grandmaster failover introduced only brief microsecond-level transients that did not affect robot stability. Such robustness is crucial for industrial environments where timing infrastructure must operate continuously despite network load variations or external disturbances.Overall, the findings reinforce that sub-microsecond 5G synchronization provides a strong foundation for next-generation smart factories. It enhances robot precision, improves cycle-time repeatability, and supports scalable, heavy-automation environments. By combining 5G, PTP, and TSN technologies, industries can transition from rigid wired control systems to flexible, wireless, and deterministic automation platforms. This work establishes a blueprint for deploying highly synchronized 5G-enabled robotic systems capable of meeting the demanding requirements of Industry 4.0 and future autonomous manufacturing ecosystems.

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